

Performance Analysis of a Wind Turbine Driven Swash Plate Pump for Large Scale Offshore Applications

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Abstract. This paper deals with the performance modelling and analysis of offshore wind turbine-driven hydraulic pumps. The concept consists of an open loop hydraulic system with the rotor main shaft directly coupled to a swash plate pump to supply pressurised sea water. A mathematical model is derived to cater for the steady state behaviour of entire system. A simplified model for the pump is implemented together with different control scheme options for regulating the rotor shaft power. A new control scheme is investigated, based on the combined use of hydraulic pressure and pitch control. Using a steady-state analysis, the study shows how the adoption of alternative control schemes in a the wind turbine-hydraulic pump system may result in higher energy yields than those from a conventional system with an electrical generator and standard pitch control for power regulation. This is in particular the case with the new control scheme investigated in this study that is based on the combined use of pressure and rotor blade pitch control.

1. Introduction

Current research is evaluating the possibility of having replacing the electrical generator on individual wind turbines by a large positive displacement pump. Rather than producing electricity directly, the individual wind turbines would pump seawater under high pressure to a centralised hydro-electric station. This concept is expected to offer some other important advantages in offshore wind exploitation: it would facilitate the integration of wind power with wave power extracting devices, energy storage systems and reverse osmosis desalination plants. Hydraulic energy is also much easier to store compared to electrical energy. A hydraulic energy storage system can be as simple as pumping seawater into reservoirs, where the energy is stored in the form of a pressure head. This is much simpler and more effective when compared to battery banks, which are not only significantly more expensive, but also detrimental to the environment since they require the use of hazardous chemicals. A hydraulic transmission system will also reduce the use of copper.

The main objectives of this paper are to:

- Review current developments in the field of hydraulic-based offshore wind turbines.
- Present a simple mathematical model for steady-state performance simulation of an open-loop system pumping pressurised sea water under steady wind conditions.

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- Compare the performance characteristics of the open-loop system under different control schemes, including a newly proposed scheme relying on the combined use of rotor pitch and hydraulic pressure control.

The present study draws inspiration from a radical new approach being put forward by researchers at the Delft University of Technology (TUDelft) [1]. Diepeveen [2] states that present offshore wind turbines are merely land-based turbines with some modifications to mitigate seawater degradation. Progress in standard technologies has only been of an incremental nature. A number of companies have already begun research and development in the field of hydraulic driven systems for large-scale wind turbines. ChapDrive [3] is a Norwegian company developing a gearless drive system for wind turbines. A low speed radial pump replaces the gearbox and connects to a high-speed hydraulic motor, which in turn connects to a synchronous generator. The generator can either be situated in the nacelle or at the base. This system allows for operation at a continuously variable gear ratio. The control system is designed to simultaneously regulate the pitch, torque and generator excitation of the system. Some advantages that the company claims are a 20% reduction in the cost of power, a simpler, more reliable system without any gearboxes, frequency converters or transformers, and a significant reduction in nacelle weight [3]. They have successfully tested 225 kW and 900 kW turbines. The company has recently erected a 5 MW turbine [3].

Artemis Intelligent Power, Ltd. [4] is a Scottish company specialising in Digital Displacement[®] Transmission (DDT). This design normally consists of radial pumps and motors that use high-speed solenoid valves for displacement control. The company was recently acquired by MHI (Mitsubishi Heavy Industries, Ltd.) that plans to implement the DDT[®] technology in a 7 MW offshore wind turbine called SeaAngel[™]. This turbine will use a setup similar to the ChapDrive system, with synchronous generators in the nacelle, coupled to the rotor through a hydraulic transmission system [4].

The two prototypes described above have both implemented hydraulic systems into wind turbines, however they have not really made any attempt to utilise seawater as a hydraulic fluid. The latter concept is being addressed by the Delft Offshore Turbine (DOT) [1,2]. Seawater has a relatively high bulk modulus, reducing compressibility losses. It is also abundant and at a steady low temperature, eliminating the need for a working fluid cooling system.

The application of hydraulic drives to wind energy is definitely not a new concept. Early works by JERICO (1981) and L. Rademakers (1988) evaluated this possibility and listed lack of component availability as the main problem [5]. Hydraulic systems are not typically designed for the scale and efficiency required for offshore wind generation. For example, the DOT will require pumps with a flow capability of 10,000 litres/min [6]. Theoretical and experimental predictions indicate that the technology can be developed to handle such a flow requirement [6]. With the potential for better reliability and an improved power-to-weight ratio, they are becoming an attractive solution.

To date, simulations have been based on a conceptual turbine with a combination of a closed-loop and an open-loop transmission, a system discussed by Diepeveen [6]. A pressurized oil circuit transfers energy from the nacelle to the base using a radial piston pump and a hydraulic motor. At the base, the motor turns a variable displacement swash plate pump that draws in seawater and transfers it to a centralised hydroelectric generation platform. Results from these simulations, as indicated by Laguna [5], are encouraging if one considers the use of alternative control schemes.

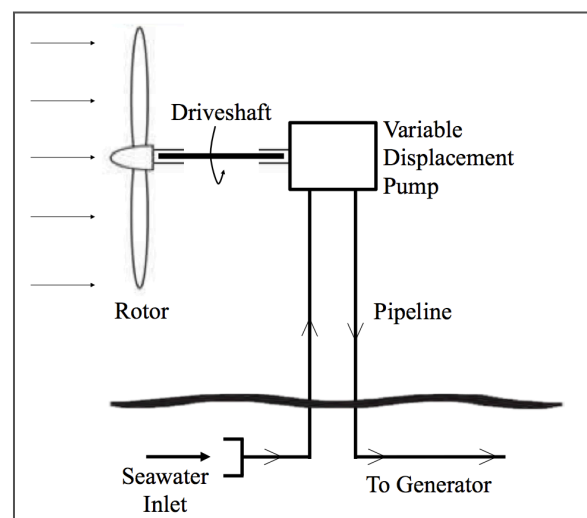


Figure 1: A schematic of the system being analysed.

The present study utilises the same principles, but further simplifies the system and introduces the notion of a combined rotor-pitch and hydraulic-pressure control scheme. Simulations are carried out using a model of the same NREL 5MW [7] rotor that was used by Laguna at TUDelft [5]. However, in this case, a single open loop system is considered, with the swash plate pump situated in the nacelle and directly connected to the rotor. A schematic is shown in Figure 1.

Control schemes identical to those used at TUDelft [5] are simulated, along with a new approach utilising pressure control in the hydraulic circuit. The operating efficiencies are comparatively high when compared to present electrical systems. They are actually superior at higher wind speeds yet still comparable at lower speeds. These results indicate the potential for incorporating pressure control systems into the wind farm design.

2. Theoretical Background

The analysis of the proposed system starts with a derivation of the mathematical equations that model the performance of the system shown in Figure 1. The model caters for the overall power performance of the system: from a rotor aerodynamics model to simulate the rotor shaft torque and angular velocity at a given wind speed to pipe flow models to calculate the pressure at the base of the turbine, taking into consideration fluid friction in the piping. The pump is simply treated as a black box: receiving torque at an angular velocity from the rotor and supplying seawater at a given pressure and flowrate.

2.1. Modelling Technique: The Physical Network Approach

By definition, power can be broken down into a *through-variable* and an *across-variable*. This notion forms the basis of the *physical network approach* for modelling [8]. In the case of the mechanical system (rotor-shaft-pump) these are angular velocity and torque respectively. For the hydraulic system (pump-pipeline-load) these are flow-rate and pressure difference. The approach is based on the theory that all members of a sub-system must share the same value of *through-variable*, that is, the rotor, drive shaft and pump must always have the same angular velocity. On the other hand their individual characteristics determine the *across-variable*, such as the torque loading on the shaft. The physical network approach allows for a modular approach to the modelling of physical systems and is ideal for mathematical models that will require computational implementation [8].

2.2. Aerodynamic Modelling

The Blade-Element-Momentum theory was used to model the interaction of the wind stream with the rotor blades and hence calculate the generated power at the rotor shaft for a particular wind condition and rotor angular speed. The Prandtl tip/root loss corrections were implemented in the model to account for the reduced power resulting from the loss of lift at the tip and root of each rotor blade.

2.3. The NREL 5MW Rotor

The performance model utilised the NREL 5MW Baseline Wind Turbine, a large-scale wind turbine design that was developed by the National Renewable Energy Laboratory (NREL) [7], and which served as a reference turbine for a number of international research projects. The control scheme for the NREL 5MW Baseline Wind Turbine is a standard active pitch control scheme. The main characteristics of the turbine are listed in Table 1 below.

Table 1. Rotor Characteristics of the NREL 5MW Baseline Turbine.[7]

Rating	5 MW
Rotor Orientation	Upwind
Number of Blades	3
Control	Variable Speed, Collective Pitch
Rotor, Hub Diameter	126m, 3m

Table 1 cont. Rotor Characteristics of the NREL 5MW Baseline Turbine. [7]

Hub Height	90m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4m/s, 25 m/s
Cut-In, Rated, Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip speed	80 m/s
Maximum Power Coefficient (C_{P-max})	0.482
Optimum Tip speed Ratio (λ_{opt})	7.55

2.4. Overall System Model

The system shown in Figure 1 is broken down into its fundamental components:

- Rotor
- Drive Shaft
- Variable Displacement Pump
- Pipeline (up and down the turbine nacelle)

Each subsystem is analysed separately and individual models are combined using the physical network approach. The following equations correspond to the components listed above. Together they constitute the mathematical model for the overall simplified dynamics of the system.

Equation (1) corresponds to the BEM model. The elemental torque distribution (dM/dr) is obtained as a function of wind speed (u) and rotor angular velocity ($\dot{\theta}_S$). Integration with respect to the radial dimension (dr) from the hub (R_h) to the tip (R) gives the total torque generated by the rotor (M). The standard active pitch control scheme was implemented into the BEM code as an iterative procedure that proportionally alters the collective pitch angle of the blades (β) until the required torque/mechanical power is being developed by the rotor.

$$M = \int_{R_h}^R \left(\frac{dM}{dr} (u, \dot{\theta}_S, \beta) \right) dr \quad (1)$$

Equation (2) relates the rotor torque (M) to the torque requirement of the pump (M_{pump}), using the drive shaft dynamic parameters: inertia (J_S), damping (D_S) and stiffness (k_S). Since simulations are carried out in the steady state, dynamic terms are equated to zero. The equation was derived in this way to allow for more elaborate forms of analysis in the future.

$$M - M_{pump} = J_S \ddot{\theta}_S + D_S \dot{\theta}_S + k_S \theta_S \quad (2)$$

Equation (3) is the general equation for the ‘black-box’ model of the pump. It predicts the torque loading of the pump in terms of the pressure load applied across it (Δp), its current volumetric displacement (V_P) and the operating angular velocity ($\dot{\theta}_S$). Pump inefficiencies are accounted for by considering the total (η_{tot}) and volumetric efficiencies (η_{vol}); these would be given in a pump data sheet along with the nominal pressure (Δp_{nom}) and angular velocity ($\dot{\theta}_{nom}$) at which they are valid [8].

$$M_{pump} = \frac{V_P \Delta p}{2\pi \eta_{tot}} \left\{ 1 - (1 - \eta_{vol}) \left(\frac{\dot{\theta}_{nom}}{\Delta p_{nom}} \right) \left(\frac{\Delta p}{\dot{\theta}_S} \right) \right\} \quad (3)$$

Equation (3) uses these variables to extract the operating efficiencies from the nominal efficiencies with the assumption that the leakage flow is linearly proportional to the pressure difference across the pump. This assumption allows for the use of the *Hagen-Poiseuille* [9] formula when deriving equation (3). The volumetric displacement is related to the swash plate angle (α) through equation (4) below, where n is the number of pistons, R_p is the piston pitch radius and A_p is the piston area.

$$V_p = (2nR_pA_p)\tan(\alpha) \quad (4)$$

Equation (5) below models the pressure across the pump. This encompasses the fixed pressure requirement at the hydroelectric generator (Δp_L) and the frictional load as a result of the fluid travelling up and down the turbine. The latter is expressed in terms of the operating flow rate, ie: fluid density (ρ), pipeline length (L), internal diameter (D) and flow friction factor (f). This factor is obtained from the Reynolds Number either from the laminar flow equation ($f = 64/Re$) or using the Colebrook and White equation [9] in the case of turbulent flow.

$$\Delta p = \left(\frac{2fL\rho}{\pi^4 D^5} \right) \left(\dot{\theta}_S - (1 - \eta_{vol}) \left(\frac{\dot{\theta}_{nom}}{\Delta p_{nom}} \right) \Delta p \right)^2 V_p^2 + \Delta p_L \quad (5)$$

The model has five unknown parameters (M , $\dot{\theta}_S$, M_{pump} , V_p and Δp) and five equations. The equation set is a function of a single independent variable: the wind speed (u). The rest are constants to be obtained from geometrical parameters or pump data sheets and a set of variables to be determined. With the proposed open-loop system, a priming/boost pump would be required given the height of the main pump located inside the nacelle. This pump was neglected in the analysis, since the energy required to lift the seawater to the 90 m hub height level was found to be less than 2% of the energy supplied by the main pump.

2.5. Computational Modelling

A computational model was created, based on the derived mathematical model. The program simulates the overall system (all relationships encompassed in equations (1) to (5)). It can be used to determine the relationship of numerous system parameters with wind speed. The program is used to simulate the different control schemes at the operational range of wind speeds. Its main limitation is that the pump is modelled as a “black-box” as discussed in the mathematical modelling. The overall system model was implemented using Matlab and the Simscape package within Simulink [8].

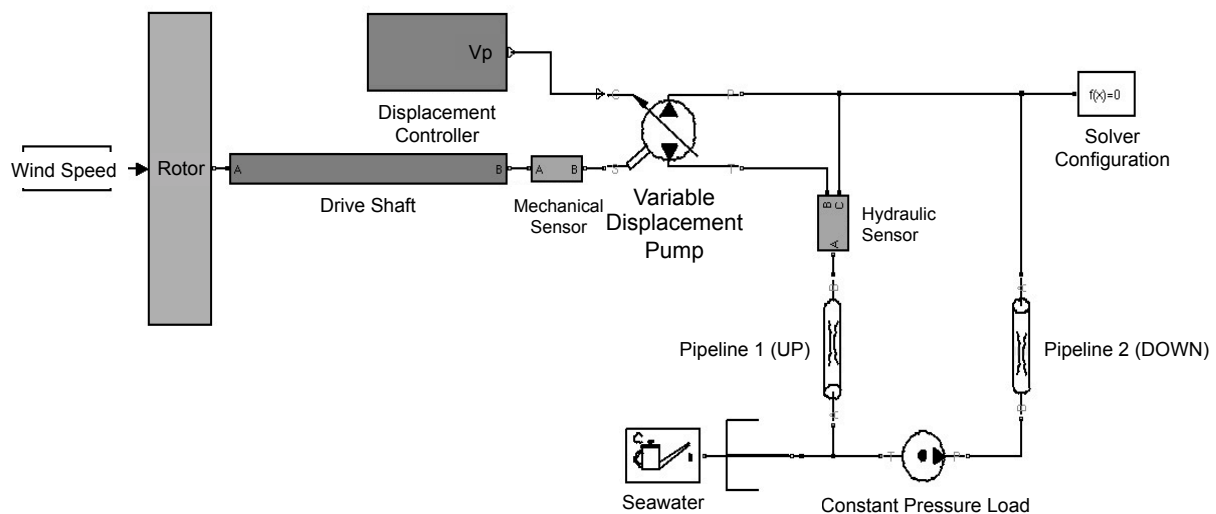


Figure 2: Typical structure of a Simscape model [8]. Shown above is Overall System Model

3. Control Schemes

The operational limits of the proposed design were not restricted to the power rating of the electrical generator. On the other hand, the study investigated how the same 126 m diameter rotor could harvest more power than the rated value of the electrical generator by replacing the latter with a hydraulic pump and altering the control scheme. Equation (3) shows how the torque loading of the pump is directly proportional to the variable displacement, therefore the swash-plate controller can be used to speed up or slow down the rotor as required via negative feedback control. This method of control is used up to the rated wind speed (u_{rated}), where the pump reaches its maximum volume. Beyond this limit, three other schemes of control are used as described briefly below. Different controller options are tested under the *steady-state* condition. Therefore the scope of the analysis is limited to obtaining the final behavior of the system, in the form of the power-curve that would result from the use of the different control schemes.

3.1. The Standard Pitch Control Scheme.

This is the standard pitch control scheme used in typical variable speed wind turbines. It is simulated to directly compare the performance of a standard wind turbine to a hydraulic wind turbine. The design of this control scheme is driven by the limitations of electrical generators and therefore it is not the optimal control solution for a pump-based turbine.

Table 2. The Standard Pitch Control Scheme.

	Pitch Controller	Torque Controller	Controller Aim
$u_{\text{cut-in}} < u < u_{\text{rated}}$	Inactive	Operational	Optimize C_p
$u_{\text{rated}} < u < u_{\text{cut-out}}$	Operational	Inactive	Maintain Constant RPM

3.2. The High Speed Scheme.

This scheme that has been developed by TUDelft [6] allows the turbine to reach a higher angular velocity beyond the rated wind speed up to a particular limit ($u_{\text{lim-1}}$). The aim of the pitch controller in Mode 1 is to keep a constant torque while allowing the angular velocity, and hence power generated, to increase. Beyond this limit the standard pitch control scheme is adopted (Mode 2), where the angular velocity is fixed to limit power.

Table 3. The High Speed Scheme [6].

	Pitch Controller	Torque Controller	Controller Aim
$u_{\text{cut-in}} < u < u_{\text{rated}}$	Inactive	Operational	Optimize C_p
$u_{\text{rated}} < u < u_{\text{lim-1}}$	Operation Mode 1	Inactive	Maintain Constant Torque
$u_{\text{lim-1}} < u < u_{\text{cut-out}}$	Operation Mode 2	Inactive	Maintain Constant RPM

3.3. The Combination Scheme.

In this scheme, pressure-based and blade-pitch control are combined. Increments in the supply water pressure are used to increase torque loading up to a certain limit, maintaining a fixed angular velocity while still increasing power generation. Beyond this limit ($u_{\text{lim-2}}$) standard pitch control is adopted to limit power. This is a new approach being investigated in this study for the power regulation of hydraulic wind turbines.

Table 4. The Combined Pitch and Pressure Control Scheme.

	Pitch Controller	Pressure Controller	Torque Controller	Controller Aim
$u_{\text{cut-in}} < u < u_{\text{rated}}$	Inactive	Inactive	Operational	Optimize C_p
$u_{\text{rated}} < u < u_{\text{lim-2}}$	Inactive	Operational	Inactive	Maintain Constant RPM
$u_{\text{lim-2}} < u < u_{\text{cut-out}}$	Operational	Inactive	Inactive	Maintain Constant RPM

4. Results

Figure 3 shows that adopting a standard control scheme for this hydraulic rotor design is not ideal since beyond the rated wind speed, the hydraulic power at the turbine base is around 2% less than the electrical output of the NREL 5MW reference turbine.

The high-speed control scheme, modelled for a seawater pressure of 150 bar, clearly shows a potential for higher energy yield at the same wind speed. When compared to the standard control scheme it was also seen that the maximum induced thrust force and torque are the same. This was also observed by Laguna [5] and is due to the fact that the rotor angular velocity is allowed to increase with wind speed. It implies that mechanical loads will tend to be similar to standard designs. Another advantage is that the pitch controller can be designed to sweep a narrower range of angles when compared to the standard requirements. However, the rotor is required to operate at a significantly higher angular velocity: 19.2 rpm instead of the rated 12.1 rpm. This results in higher cycling of the structural loads, which potentially increases fatigue and wear.

The combined pressure and pitch control scheme considers the seawater pressure increasing up to 260 bar. This shows better power harvesting characteristics, however it comes at the price of having to

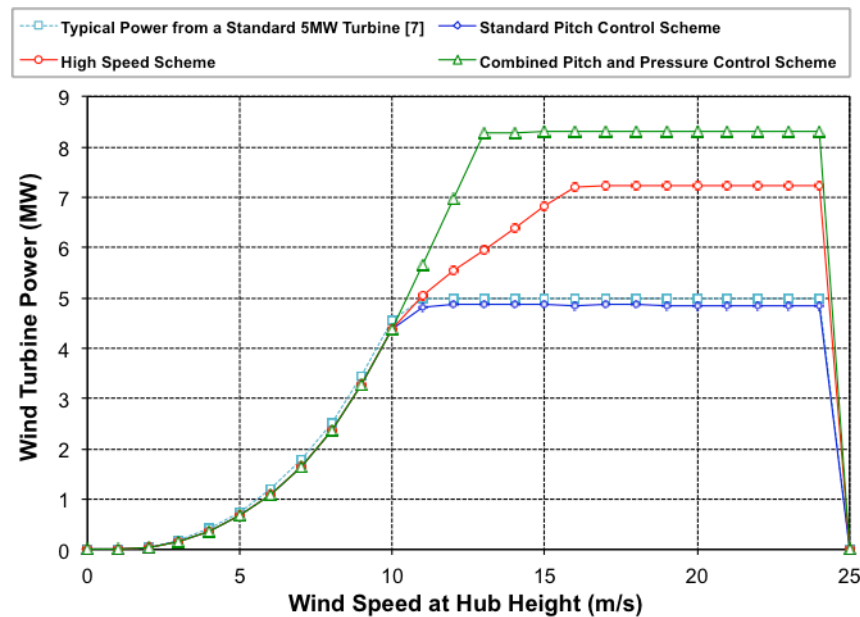


Figure 3: Power developed by the wind turbine using the different control schemes. Also shown is the NREL reference data [7].

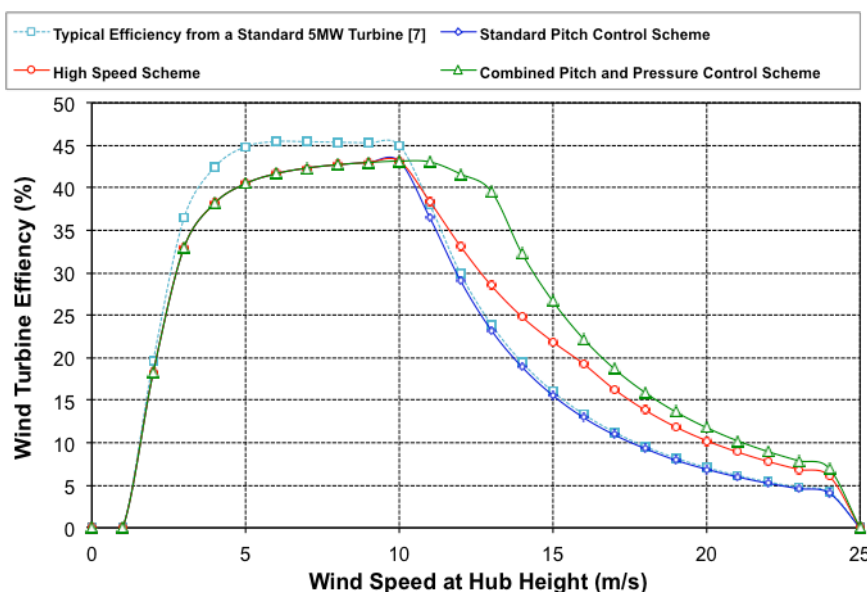


Figure 4: Turbine overall efficiency with wind speed. Also shown is the typical 5MW efficiency computed from the NREL reference data [7].

support higher seawater pressures. The structural forces on the turbine are also higher. Thrust forces on the blades are increased by 36% and torque loading on the shaft by 74%. Advantages of this scheme are that it avoids operating angular velocities higher than 12.1rpm and the pitch controller is also required to sweep through a narrower range of pitch angles when compared to the standard control scheme.

An analysis of the turbine

efficiency was carried out by considering the hydraulic power generated at the turbine base with respect to the wind power available at the rotor plane. It can be observed from Figure 4 that the hydraulic wind turbine is less efficient at lower wind speeds when compared to NREL data [7] for the standard turbine. This is attributed to the losses in the pump and pipeline. However, beyond a wind speed of 10.5m/s, the control scheme using pressure and pitch control, and to a lesser extent the high-speed control scheme, push the turbine to a much higher operating efficiency.

The annual energy yield was computed for a range of average long-term wind speeds. A Weibull distribution was assumed [10]. Table 5 shows that the annual energy yield is higher for the hydraulic based wind turbine using the high-speed scheme and the scheme using pressure and pitch control.

Table 5. Annual energy yield for the different control schemes and the NREL reference data [7].

Average Wind Speed[m/s]	Annual Energy Yield [GW-hr/annum].			
	NREL 5MW Data	Standard Pitch Control Scheme	High Speed Scheme	Combined Pitch and Pressure Control
7.0	14.8	14.0	15.3	16.9
8.0	18.3	17.4	19.7	22.1
9.0	21.3	20.4	23.7	27.0

5. Conclusion

- The current study has shown the potential of hydraulic-based wind turbines to increase the viability of offshore wind energy, particularly when coupled with alternative schemes of control that are specifically developed for this type of wind turbine.
- The use of pressure control in conjunction with pitch control is shown to provide a means for increasing the power harvesting capabilities of the turbine. However, this comes at the cost of increased structural loads on the turbine and other system components.
- This paper focused on the steady-state performance of the hydraulic wind turbine. Future work will assess the feasibility of the proposed control scheme, with a more complex model operating under transient pressure and wind conditions. An evaluation will also be undertaken to evaluate whether the additional system costs resulting from increased operational pressure limits are justified with respect to the increase in energy yield.

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